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MICRORAPTOR: A LOW-COST AUTONOMOUS QUADROTOR SYSTEM

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ABSTRACT

This paper describes Microraptor, a complete low-cost autonomous quadrotor system designed for surveillance and reconnaissance applications. The Microraptor ground station is custom-made and features a graphical user interface that presents and allows the manipulation of various flight parameters. The aerial vehicle is a 4-rotor vertical takeoff and landing (VTOL) vehicle that features the advantages of traditional helicopters with significant reduction in mechanical complexity. The vehicle frame is a handmade magnesium and carbon fiber structure. The onboard avionics system is a custom dual processor design capable of autonomous path navigation and data exchange with the ground station. The vehicle is outfitted with a video and still-photo system that provides real-time images to the system operator through the GUI. The system is being developed at Oakland University by a team of multidisciplinary undergraduate and graduate engineering students. Microraptor placed 5th at the 2008 Association for Unmanned Vehicle Systems International (AUVSI) Unmanned Aerial Systems (UAS) Competition and is set to compete again in June of 2009.

1   INTRODUCTION

This paper describes the design, implementation, and performance of *Microraptor,* a four-rotor aerial vehicle (a.k.a. quadrotor) developed at Oakland University. This low-cost UAV is capable of remote control operation, autonomous vertical take-off and landing, as well as autonomous predefined path navigation and image acquisition. Microraptor competed at the 2008 Association for Unmanned Vehicle Systems International (AUVSI) Unmanned Aerial Systems (UAS) Competition, placed fifth, and is currently being prepared for the 2009 UAS [1] competition.

The Microraptor aerial vehicle is shown in Figure 1. The avionics system is stacked in the center of the structure and manages flight control functions per instructions from a PC-based ground control station. The ground control station is a

custom-made system that presents the operator with various flight data and allows the manipulation flight paths and profiles as well as the inspection live video and high-resolution still images captured on the vehicle.

Figure 1. Microraptor Vehicle

This paper is organized as follows. The next section provides a background on quadrotors, design requirements, and related work. Section 3 discusses the design and implementation of the system and covers the vehicle structure, power plant, avionics, ground station, payload, and safety features. Section 4 presents system cost. The paper is concluded with a summary in Section 5.

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2 BACKGROUND

Early designs and prototypes for quadrotors started to appear during early 1920s [2]. These vehicles were manually controlled and exhibited poor stability and performance. In the 1950s, two prototypes were built. One was destroyed in a crash and the other one is now in the National Museum of the United States Air Force [3]. Recent advances in propulsion and energy storage technologies have however renewed the interest in quadrotors especially in the field of UAVs.

2.1 Quadrotors

A quadrotor consists of two sets of counter-rotating fixed-pitch propellers. Both the lift and the reaction torque of each propeller are used to manipulate altitude, attitude, and heading of the vehicle. Each set of blades is mounted on one axis of the cross shape vehicle as shown in Figure 2. The altitude of the vehicle is controlled by varying the speed of the four rotors collectively. Assuming that rotor 1 is the front of the vehicle, the pitch is controlled by adjusting the relative speed between rotors 1 and 3. Similarly, the roll of the vehicle is controlled by varying the relative speed between rotors 2 and 4. Finally, the yaw of the vehicle is controlled by varying the speed of two rotors on one axis relative to the speed of the rotors on the other, while keeping the collective lift of the vehicle constant.
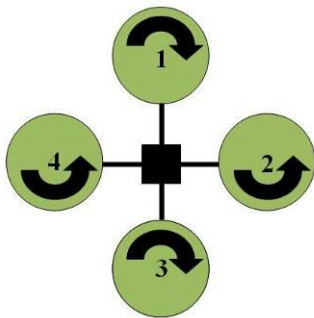

Figure 2. Quadrotor Reaction-Torque Schematic

Quadrotors have several advantages over fixed-wing planes. They are capable of hovering and flying at low speeds, which is especially useful in surveillance applications. In addition, vertical takeoff and landing vehicles (VTOLs) can be deployed in almost any terrain. Quadrotors also have multiple advantages over traditional helicopters as well. The most important of which is the reduced mechanical complexity, which enhances safety and significantly reduces manufacturing and maintenance costs.

Due to these significant advantages and the availability of computer control that is capable of stabilizing the inherently unstable airframe of a quadrotor, development of these vehicles are increasing for applications in various fields.

2.2 Design Requirements

Microraptor was originally developed to compete at AUVSI UAS competitions. These competitions are designed to provide student teams with realistic scenarios for autonomous aerial missions. The 2008 mission requirements can be summarized as follows:

i. Autonomous Take Off and Landing.

ii. After takeoff, vehicle should be steady and have flight control above 100 ft and below 750 ft.

iii. Air vehicles shall overfly selected waypoints and remain inside assigned airspace, and avoid no-fly zones.

iv. Air vehicles will be required to fly specific altitudes and airspeeds while identifying several targets along the predefined entry/exit route (some targets will be up to 250 ft away from the center of the flight path).

v. Location, shape, color, orientation, alpha, color of all observed targets should be reported.

vi. Being able to locate "pop-up" targets.

vii. Mission completion time between 20 and 40 minutes.

viii. Safety features, including switching to manual safety pilot, terminate flight, and return home systems when loosing communication.

ix. The system shall not employ any ground based sensors.

x. The system shall be capable of commanded altitude changes.

xi. The system shall be capable of commanded airspeed changes.

xii. The system should have the capability to adjust mission search areas in flight.

Two motivations were behind choosing a quadrotor design to participate in the UAS competition. The first motivation is our research interest in 4-rotor UAVs. Secondly, the uniqueness of the vehicle helped secure funding as well as motivate many students to volunteer by getting involved in the project.

An initial search was performed to find a suitable quadrotor on the market. The search process found quadrotors which were either too small with insufficient payload capabilities, or they were too expensive (cost more than $10,000). The first option was discarded since such small vehicles cannot carry the required payload to perform the previously mentioned requirements (around 1 kg). Since the second option was too expensive for a student's project, the decision to build the Microraptor was made.

2.3 Related Work

There are several research efforts focused on specific topics relating to the operation of quadrotors, similar to those implemented on the Microraptor. For example, Pedro [4] and STARMAC [5] are recent quadrotor test-beds that are based on small commercial radio controlled products such as the Draganfly [6]. These vehicles are smaller in size and can carry only a limited payload. A larger, custom designed quadrotor is the STARMACII by Stanford [7], which is equipped with an IMU, GPS for stabilization and navigation control, and a sonar range finder for accurate altitude measurement. The recently developed STARMACII as well MARKII [8] and work by Pund *et al.* [9] are focusing on modeling and attitude control of quadrotors. In contrast, our goal was to develop a complete quadrotor system using the knowledge developed by related research efforts and add autonomous operations ability as well as meet the UAS competition requirements.

3 DESIGN AND IMPLEMENTATION

Microraptor consists of two subsystems as shown in Figure 3: a ground station that is responsible for flight control and data processing, and the aerial vehicle, which features a dual processor avionics system and carries a wide-angle video camera system and a high-resolution still camera. The two subsystems are connected by three wireless links. Telemetry and control data are exchanged using a 2.4 GHz link. The second link is a 1.3 GHz channel for video recording and processing. The third link is a standard FM hobby remote control link that serves as a backup and allows manual override of the autonomous flight system for safety.
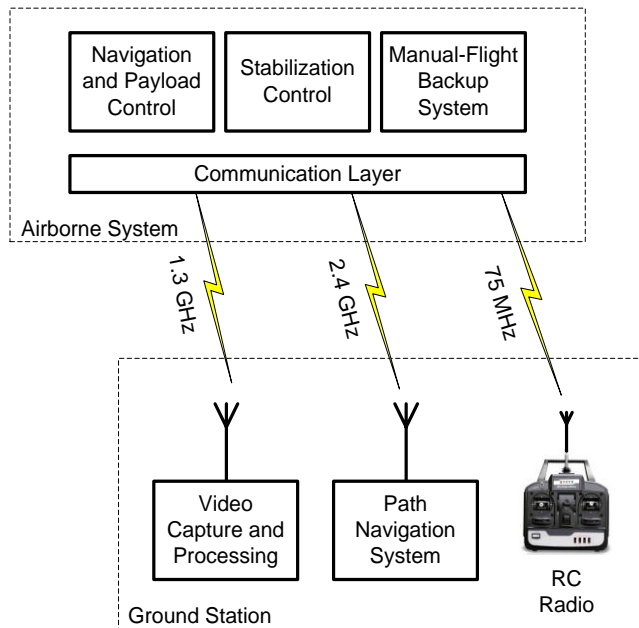

Figure 3. A High-Level View of Microraptor

In comparison with other types of aerial vehicles such as fixed wing airplanes, the payload capacity of the quadrotor is significantly smaller. The weight, size, power requirements, and performance of all components were therefore carefully considered in the development process of Microraptor. The following subsections will cover the various system components in more detail.

3.1 Vehicle Structure

The body of the Microraptor is shown in Figure 4. It consists of a magnesium hub joining four carbon fiber arms. Mounted at the end of each arm is a magnesium motor mount that holds a brushless motor and propeller assembly. Fixed underneath each motor mount is a landing strut made of flexible steel blades. The resulting physical structure weighs approximately 1400 grams and measures 40 x 40 cm (without propellers). The carbon fiber rods used have a tensile strength of 200,000 psi and a density of 1.49 g/cm^3. The carbon fiber structure is conductive so caution was taken to make sure that no wiring came into contact with the frame.

Figure 4. The Quadrotor Frame with Motors and Landing Struts

3.2 Power Plant

Four Hacker A20-20L outrunner brushless motors were used to drive the system. Outrunner motors are highly efficient. Each motor weighs around 57 grams and consumes up to 150 watts of power. This motor features oversize bearings, curved neo-magnets, and high efficiency stator design. The A20-20L was originally developed for slow-flying 12-18 oz Parkflyer models. This 12-pole motor creates significant torque at low speeds and can thus drive direct props without the need for a gearbox.

The vehicle uses two sets of counter rotating blades, which are uncommon. The commercial availability of such propellers with the desired length and pitch is limited to one brand, which are the 10'' x 4.5'' EPP1045 propellers from MAXX Inc. Using the selected motors and propellers, the quadrotor is capable of maximum theoretical liftoff weight of 2.2 kg.

As a power supply for the motors and all other electronic devices, lithium polymer batteries are used due to their exceptional power to weight ratio. Two FlightPower Evolite 5350 3S were installed. The total battery package weighted 760 grams which comprises around 35% of the total weight. The package has a 10,700 mAh capacity, which is capable of providing around 15 minutes of flight time.

3.3 Avionics

The avionics system (show in Figure 5) is a dual processor design capable of autonomous path navigation and data exchange with the ground station. Figure 6 shows a general flow chart describing the different avionic components and the communications between them. The telemetry processor is responsible for data monitoring and collection from the sensors. The collected data is shared with the control processor, which is responsible for vehicle stabilization and navigation, as well as wirelessly transmitting data to the ground station. The monitoring function, which is installed on the control processor on the other hand, allows the detection of failures in the system (e.g. low battery, excessive altitude change rate, and vehicle instability) and initiates emergency landing procedures when warranted.
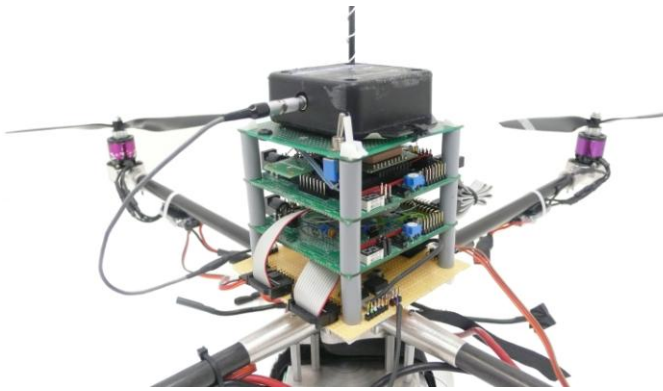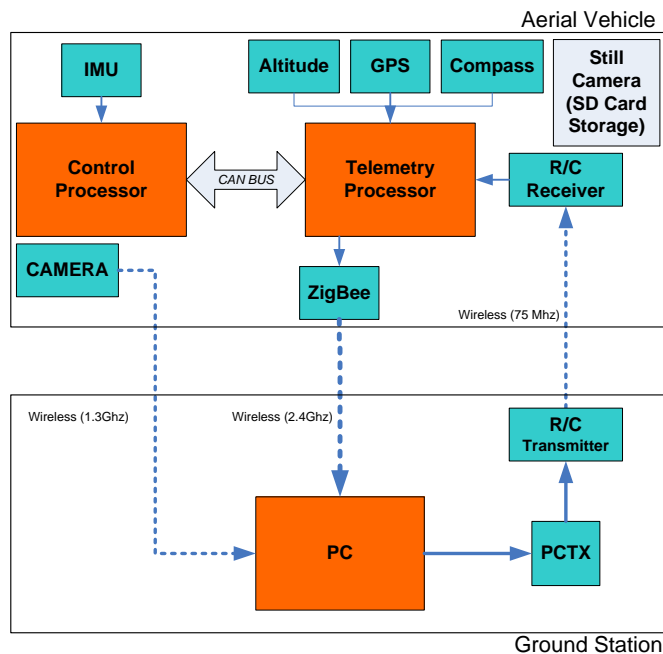
Figure 5. The Quadrotor Avionics

Figure 6. General System Overview

To ensure reliable communication between the two processors, a 1 Mbps controller area network (CAN) interface is used. The advantage of using CAN is the robust design in addition to the availability of message buffers that can hold data until it is needed by the processors. A ZigBee module is used to relay data between the vehicle and ground station. The telemetry packets are 77 byte frames and contain all the vehicle flight data (i.e. IMU, GPS, Altitude) in addition to some error and flow contol data. The following sections provide more detail on each avionics component.

IMU: The inertial measurement unit (IMU) provides vehicle attitude estimates to the control processor. The MicroStrain's 3DM-GX1 module was selected for this task. It is a very sensitive module that incorporates both accelerometers and gyroscopes to estimate attitude. This particular module also features a compass and a temperature sensor. The IMU can output a variety of data types and formats but only the gyro

stabilized Euler angles are used in the system. These angles estimate the absolute yaw, roll, and pitch of the vehicle. The IMU estimates are gyro stabilized and therefore have good vibration tolerance. The IMU sends its data on the serial bus at 38400 Baud to the control processor. A higher baud rate was possible, but the medium speed was chosen as a balance between reliability and speed. There are 11 bytes of data including data flow and error control information every 13 ms. Data transmission takes ~2.5 ms, which leaves 10.5 ms as the PID control loop periods.

Altimeter: Altitude is determined using a SMD500 Barometer Breakout Board from Bosch Sensortec. This board is very light at around 1.5 g. The altimeter data is sent through an I^2C interface to the telemetry processor. For takeoff and landing purposes, an ultrasonic range finder (MB1040) made by Maxbotix, Inc. with a range of approximately 6.45 m is used. The range finder output is captured using a pulse width modulation (PWM) module on the telemetry processor.

GPS: The path navigation is based on an integration GPS onboard. Most integrated GPS modules have comparable performances. The precision of a GPS unit can be enhanced by good antenna placement on the vehicle. Thus our focus shifted to find the GPS module with the lowest weight. Two designs are available from Ublox: the C04-4H and the C05-5H. The C04-4H was chosen because testing showed that it has higher precision than the C05-5H model. The C04-4H has a low weight and an efficient antenna that does not require much space. The GPS module has 37 mm x 37 mm x 9.0 mm dimensions.

Telemetry Processor: The telemetry processor has multiple responsibilities. It is a Freescale HCS12 microcontroller that reads the GPS, altimeter, compass, and the PWM capture from the RC receiver and assembles a data frame to be sent back to the base through the ZigBee link for control feedback. The processor also provides the control processor with IMU, compass, altitude, and data in addition to command signals from the ground station. Heading and altitude commands from the ground station are translated into desired altitude, pitch, and yaw values and passed to the control processor.
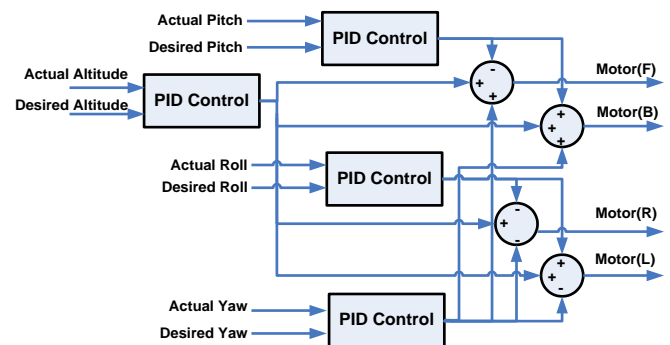

Figure 7. Control System Diagram

Control Processor: The control processor is also a Freescale HCS12 that is responsible for vehicle stabilization. It reads the Euler Angles from the IMU and control signals from the telemetry processor and performs Proportional-Integral-

Differential (PID) control loops. In this project, four PID control loops are used to stabilize and control the vehicle (Figure 7). The motor speed is controlled by the PID control loops according to the throttle, pitch, roll, and yaw values received by the IMU, GPS unit, and altimeter. In the PID control loops, the current errors are calibrated with PID gain constants Kp, Ki, and Kd to generate the proper motor adjusting values where Kp, Ki, and Kd are the proportional, integral, and differential gain constants respectively. The PID gains are found experimentally, and our system allows wireless update of the PID gains to allow in-flight tuning.

Figure 8 shows a sample pitch response of Miroraptor. The figure, which is a screenshot of the Vector CANalyzer™, is a plot of two signals: the command or desired pitch signal (Des_Pitch) in degrees, and the IMU_Pitch signal, which is the actual pitch response to that command measured by the IMU. Figure 9 shows the command roll signal (Des_Roll) in degrees as well as Microraptor's Roll response measured by the IMU (IMU_Roll). Similarly, yaw command and response in degrees are shown in Figure 10.
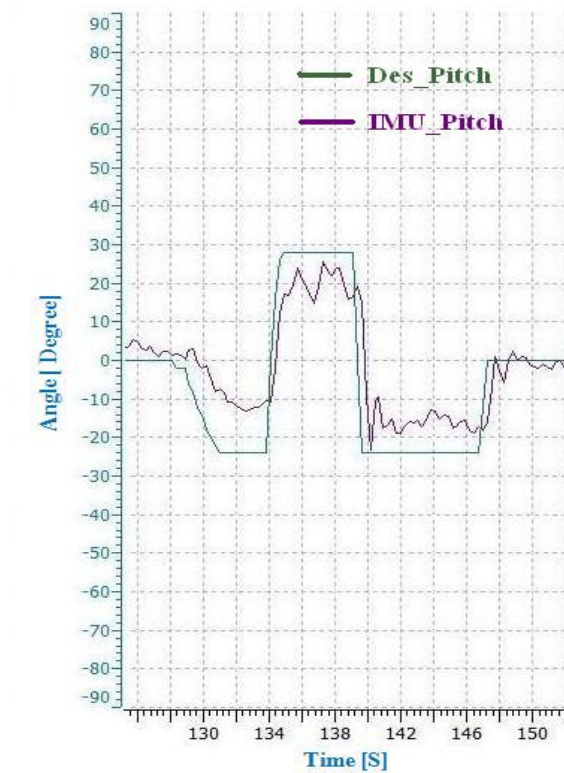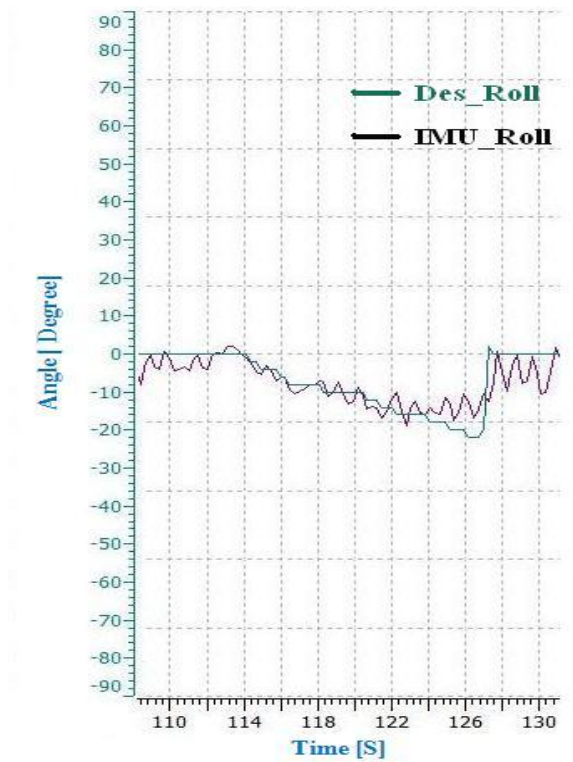

Figure 9. Sample Roll Response
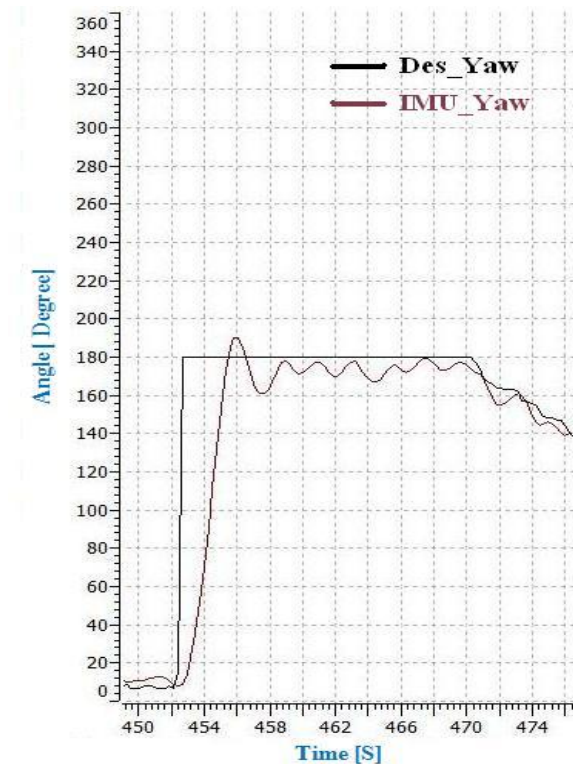

Figure 8. Sample Pitch Response

Figure 10. Sample Yaw Response

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3.4 Ground Station

The PC ground station software, shown in Figure 11, is primarily responsible for navigation and image processing. The software was developed in C#. It displays received telemetry, allowing the setting of navigation waypoints, and it periodically computes new heading and altitude setpoints. The PC ground station receives the telemetry string form the vehicle containing GPS, altitude, and heading data through a ZigBee to RS232 converter. The software has a user friendly interface for setting up a flight path and viewing various data received from the quadrotor.

The setpoints for altitude and heading are periodically computed by the ground station software and sent up to the vehicle through the trainer input (a.k.a. buddy cable input) of the R/C transmitter that is connected to the PC through a custom interface circuit.
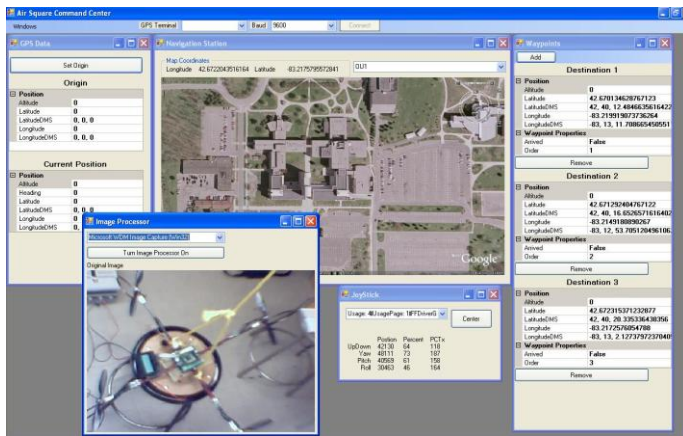

Figure 11. Ground Station GUI

The received data are passed on by the onboard telemetry processor to the control processor. Translation of data frames received from the ground station is performed by the telemetry processor and results in only three setpoints that are passed to the control processor. These setpoints are: desired altitude, desired pitch, and desired yaw. The quadrotor vehicle is capable of precise altitude control, so the desired altitude data is passed as received from the ground station. Based on the actual lateral position as determined by the telemetry processor and the desired lateral position received from the ground station, a new heading is computed and passed to the control processor in form of a desired yaw value. The quadrotor is designed to either hold position or move forward by pitching down by $10°$ from the horizontal (i.e. always traveling at a fixed airspeed) and to hold roll at $0°$ at all times. The vehicle therefore moves towards waypoints by periodically adjusting vehicle yaw while traveling at a constant speed.

3.5 Payload

The payload includes two vision systems: a video system and a still photo system. The video system will send live video to the ground station during all mission time. However, the still photo system is used for on demand high-resolution images.

The video system is composed of a CCD (Charge Coupled Device) camera, a transmitter, and a ground station receiver. This system operates at the 1.3 GHz bandwidth. The camera has a 1/3 inch Sony CCD, weighs 22 grams, and has a 420 TVL horizontal resolution. The transmitter has a 300 mW power capacity capable of transmitting video signals over one mile.

The video ground station is composed of a receiver and an 8 dBi patch antenna that extends the reception of video signals by 0.5 miles allowing capturing signals up to 1.5 miles. The patch antenna is mounted on a two-axis system controlled by an HCS12 microcontroller that is interfaced to the ground station PC. The patch antenna is automatically directed to the video transmitter that is mounted on the quadrotor for extended range and low signal-to-noise ratios.

A video receiver on the ground captures analog video signals using a Dazzle™ Video to USB converter. The video signals to be analyzed are stored in avi (audio/video interleaved) format on a computer. GPS data is stored and correlated with the video recording by the ground system to allow for position estimation of targets of interest.

The still photo system is a FlyCamOne2 camera from ACME with an onboard SD card. The camera's dimensions are 40 mm x 80 mm x 14 mm and has a weight of 1.3 ounces. The camera is capable of capturing still photos with 1280 x 1024 resolution.

3.6 Target Recognition

Two parallel approaches have been adopted for target recognition. The first approach uses the frames captured by the video camera system. Figure 12 shows a sample frame of the video captured at 200 ft. Matlab™ scripts were implemented to compute the coordinates for each frame based on available altitude, attitude, and GPS data from the ground station.

Figure 12. Sample Video Frame at 200 ft

The second approach for target recognition is based on the images captured by the still photo camera system. Upon landing, the captured images, which are stored on a SD memory card, are removed from the quadrotor. These images are inspected to determine possible targets. The selected pictures are loaded onto Macromedia Flash. A JavaScript program was written to trace the x-y coordinates of the mouse over a picture of the field the quadrotor flew over. The pictures are made 50% transparent, and then placed over the field. The pictures are then resized and rotated as necessary. Once all of the pictures are placed, the Macromedia Flash program is started to determine the targets locations. Once the program runs, the mouse x-y coordinates are given in degree decimals. When the mouse is placed over the targets, the x-y coordinate is recorded and then converted from degree decimals to latitude and longitude. Figure 13 shows a screenshot of the still image processing GUI.
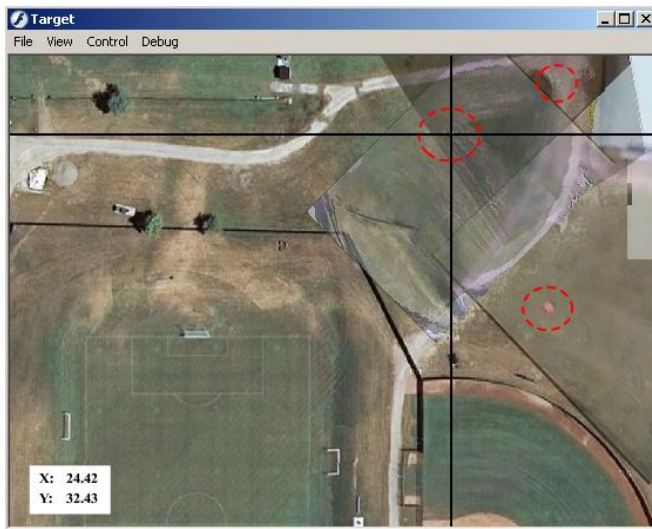

Figure 13. Macromedia Flash Program Still Image Processing GUI Showing 3 Targets

3.7 Safety

Safety was an important concern during the design. The quadrotor is controlled by a standard RC transmitter that is overridden by commands from the PC. In the event of an emergency, the signals coming from the PC can be switched off and the quadrotor can be controlled manually by the same RC transmitter. Also, if at any time the quadrotor stops receiving a signal from the RC transmitter, it will slowly power itself down and land safely. Similarly, the landing procedure is initiated if the radio signal is not received by the telemetry processor for more than 30 seconds.

As an added safety feature, all data frames passing between the microcontrollers use checksum bits. The checksum will ensure perfect data transfer and optimal operation. In case any error occurs at any frame, it is reported and the frame is discarded.

4 COST

One of the most critical designed constraints of Microraptor was component cost. Using the proposed design of the Microraptor, one can get a high quality, reliable quadrotor with no more than $3,000. Table 1 summarizes the major components used in the Microraptor along with the cost and the part number.

Table 1. Parts Used to Build Microraptor and their Costs

Part	Part module/number	Unit Price (US dollars)
4 x Bruhless Motors and Controllers	Hacker A20-20L	95
Carbon Fiber	0.500"DIA x 48"L Rod	100
2 x MCU	HCS12 Evaluation Boards	99
IMU	Microstrain 3DM-GX1	1400
Altitude sensor	Bosch SCP1000	54
Sonar sensor	MaxSonar-EZ2	27
GPS	Ublox C04-5H	199
Video System	RangeVideo AVS-1300-300	200
2 x Lithium polymer Battery	EVO LITE 5350	250
	Total Cost	$3000

5 CONCLUSION

Advances in microcontroller and energy storage technologies revived the concept of quadrotors for UAS applications in recent years. This paper described the design, implementation and performance of Microraptor: a low-cost quadrotor system that is designed for surveillance and reconnaissance applications. The system's performance is promising. Microraptor was successfully tested on June 19th in the AUVSI Unmanned Aerial Systems Student Competition where it placed 5th out of 13 teams.

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